PREDICTED VS. ACTUAL ENERGY SAVINGS OF RETROFITTED HOUSE

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ABSTRACT

This paper reports the results of actual energy savings and the predicted energy savings of retrofitted one-story house located in Dhahran, Saudi Arabia. The process started with modeling the house prior to retrofitting and after retrofitting. The monthly metered energy consumption is acquired from the electric company archives for seven years prior to retrofitting and recording the actual monthly energy consumption of the post retrofitting. The house model is established on DOE 2.1. Actual monthly energy consumption is used to calibrate and fine-tuning the model until the gap between actual and predicted consumption was narrowed. Then the Energy Conservation Measures (ECMs) are entered into the modeled house according to the changes in thermo-physical properties of the envelope and the changes in schedules and number of users. In order to account for those differences, electrical consumption attributed to A/C in summer was isolated and compared. The study followed the International Performance Measurement & Verification Protocol (IPMVP) in assessing the impact of energy conservation measures on actual, metered, building energy consumption. The study aimed to show the predicted savings by the simulated building model and the actual utility bills' analysis in air conditioning consumption and peak at monthly load due to building envelope.

Nomenclature

Y = A/C electrical consumption due to building envelope
A = A/C electrical consumption during cooling season
B = Non A/C electrical consumption during neutral season
C = Heat gain from people
COP = 1.7

INTRODUCTION

Taking advantages of building energy simulation model is a cost-effective means of evaluating energy conservation measures (ECMs). There are several well-known and tested simulation models such as DOE 2.1, BLAST, and ENERGY PLUS. These simulation models have been validated and calibrated then used in several buildings (ASHRAE, 1999 and Marc-Antoine, et al, 2001). Most new building energy simulation software has been validated through several studies, and DOE 2.1 is the most widely validated and used in energy simulation studies (Sullivan, 1998). All are based in a model representation of the building thermo-physical characteristics and mode of operations.

The main concern when using these models (software) is the accuracy and uncertainty of the predicted performance (Heidell, et al, 1985 and Haberl, et al, 2004). The modeling software may lack algorithm to simulate subsystem of the building or the weather file used in simulation is different from the weather of the period of the metered data (Jamieson, et al, 1989). The accuracy of the simulation model or its sub-components (software) is another contributing factor that may affect the accuracy of the predicted values (Heidell, et al, 1985). The thermo-physical characteristics of the building and the operation of the building contribute to the uncertainties because of the interaction between the users and the component of the building as a system (Pedini, et al, 2002). The total electrical energy consumption of an existing building should be predicted within 10% of monthly metered values and 15% of the daily values (Zmeureanu, et al, 1999). A fully informed audit of the base model can improve the accuracy of the predicted energy savings from ECMs (Jamieson, et al, 1989). The surveyed literature indicated that most of the calibration of the building energy simulation models are based on short-term metered data (Lunneberg, 1999, Yoon, et al, 1999 and Jamieson, et al, 1989).

Calibrating an energy simulation model (software) for specific project may improve the accuracy of the predicted energy savings from applying energy conservation measures (ECMs) (Heidell, et al, 1985). The user develops the base model of the house using the available information about the physical characteristics, the operating conditions and the people's energy-related behavior. The base model is then calibrated by modifying some parameters with unknown or uncertain values, based on a reasonable professional justification (Zmeureanu, et al, 1999 and Al-Mofeez, 1991). Sometimes, apparent agreement with metered data may result from compensating errors (Heidell, et al, 1985).

Several calibration studies indicated an improved accuracy of the predicted value. For example, the agreement in monthly values within 15% and annually could reach 1% difference between predicted and measured values Figure 1 (Jamieson, et al, 1989).

The number of calibration methods is as many as the studies reported in the literature. There is no standard method for calibration; however, ASHRAE stresses a full one to two year period of metered data must be obtained. These data must be matched month by month for calibration. In addition, the thermal and electricity usage characteristics of the building and its energy consumption as a time-varying function of ambient condition and occupancy must also be determined (ASHRAE, 1999).

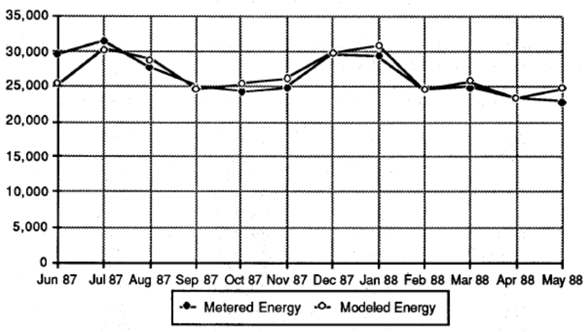

Figure (1) Comparison of fully-informed audit baseline with historical metered data.

A brief description of the process to calibrate DOE 2.1E is given to model the house. Then several runs were made to predict the actual electrical energy consumption after (ECMs). The model calibration is based on long-term metered data.

Most of the theoretical and simulation studies show the benefits of ECMs (Al-Khoutani, 2001). Home owners became cynical when asked about ECMs for energy conservation and were difficult to sway. They need a working example they can examine and to actually see the benefits of ECMs. The agreement of the calculated savings from actual metered data with the predicted results may raise engineers' and architects' confidence in energy simulation software and encourage them to utilize Computer Aided Design (CAD) in the schematic design stage. Also, the agreement of results will increase demand for energy services, especially consultants in energy modeling and simulation.

THE HOUSE DESCRIPTION

The house is a one-story detached single-family unit with a built area of 315 sq. meters. It is located in Dhahran Saudi Arabia (latitude 26.27^{o} N longitude 50.17 ^{o} E), 17 meters above sea level. The Dhahran area is characterized by its severe climate. It is hot-arid starting April through June and hot-humid in July through October. The 0.4 percentile dry-bulb is 44.2^{o}C and the mean wet bulb temperature is 23.1^{o}C (ASHRAE 2009). Detailed description of the house is documented in reference (Al-Mofeez,, 2005) along with blue prints and thermal and operational characteristics (Table 1and 2) (Al-Mofeez,, 2005).

ENERGY CONSERVATION MEASURES

Four energy conservation measures were implemented at the same time. First, external rigid insulation was applied to the west and north walls and two thirds of the south wall. The east wall and one-third of the south wall had been finished with marble tiles; therefore, they were left without thermal insulation. This changed the overall walls' U-value from 2.93 to 1.6 W/sq. m K. Glass wool blanket was installed on the ceiling. This changed the overall, roof and ceiling U-value from 2.9 to 0.92 W/sq. m. K (Table 1). Second, gaps around two large doors and one small door were weather stripped. Gap width ranged between 6 to 12 mm pre ECMs and 1 to 2 mm post ECMs. Air Change per Hour (ACH) is believed to have been reduced from 1.5 to 0.5 ACH. Third, the gaps between sealing fresh air intake panels were reduced from 40 mm to about 1 mm. This measure and weather stripping neutralized the building pressure. Fourth, supply air diffusers areas and return air grills areas were balanced. The ratio prior to ECMs diffusers' area to the grills' area was 2:1. The post-ECM ratio is decreased to 1:1. For more detailed data refer to Table 1 and reference (Al-Mofeez,, 2005).

Table 1. Building and system physical and thermal characteristics (Al-Mofeez,, 2006).

Attributes	**Units**	**Prior to ECM**	**Post-ECM**	**Remarks**
Built Area	Sq. m	315	315	Calculated from as built
Glazed Area	Sq. m	34.72	34.72	6 mm bronze tinted aluminum frame
Total Door Area	Sq. m	10.8	10.8	Calculated from as built
Total Wall Area	Sq. m	289.6	289.6	Calculated from as built
Insulated Wall Area	Sq. m	0	191	East wall is not insulated
Insulated Ceiling Area	Sq. m	0	315	Calculated from as built
Solar Heat Gains Coeff.	%	71	71	Manufacturers Data
Infiltration	ACH	1.5	0.5	Estimated by the author
Overall Wall U-Value	w/m.K	2.93	1.6	Calculated by the author
Overall Roof U-value	w/m.K	2.9	0.92	Calculated by the author
Fresh Air-intake	%	20	5	Estimated by the author
Cooling Capacity, Unit 1	Tons	7.5	7.5	York split type unit

Cooling Capacity, Unit 2	Tons	10	10	York split type unit
Average A/C COP	W/W	2.2	1.7	Average for each 6-year period
Set point Temperature	Deg. C	25	25	According to previous occupant

Table 2. Load source or system attributes

Attributes	Watt	Before	After	Before Wattage	After Wattage
Washer	750	1	1	750	750
Dryer	2500	0	1	0	2500
TV	100	1	2	100	200
Refrigerator	180	1	2	180	360
Dorm Refrigerator	80	0	1	0	80
Freezer	160	1	1	160	160
Iron	1500	1	1	1500	1500
Video	60	1	1	60	60
PC	250	1	2	250	500
Vacuum	850	1	1	850	850
Stereo	35	1	1	35	35
Hair Dryer	1500	1	2	1500	3000
Electric range	7500	1	1	7500	7500
Window A/C	2000	0	1	0	2000
Toaster	700	0	1	0	700
Coffee maker	800	0	1	0	800
Cordless Phone	20	0	1	0	20
Automated Irrigation	30	0	1	0	30
Number of occupants	115	3	7	345	805
Incandescent lamp	80	42	2	3360	160
Domestic water heater	3000	1	1	3000	3000
Fluorescent lamp	80	4	42	320	3360
Total Load				19910	28370

THE INVESTIGATION

The evaluation and verification of energy conservation measure (ECMs) is not straightforward (i.e. it is not a controlled experiment). The occupants were atypical prior to and subsequent to the ECMs. The number of users and their activities were different. This case required a procedure that is more complex. Due to limited access to hourly ambient temperature, the weather conditions during the simulation, prior, and post ECMs is considered the same; although they play important role (Farouz, et al, 2004). The error induced by variation in weather may be compensated by the long term bills analysis 6 years before retrofit and 6 years after retrofit.

In order to overcome the effects of various parameters, it has been determined to isolate the effect of other parameters to evaluate the effect of ECMs. To identify the effect of ECMs on the air conditioning electrical consumption, the author calculated the non A/C electrical consumption from the five lowest monthly bills. Then, this consumption was subtracted from the seven highest monthly bills. The remaining kWh signifies the A/C electrical consumption. To identify the contribution of the building envelope to the A/C electrical consumptions, the lowest monthly bills, assumed to be the internal heat gains contribution, were identified and then divided by Coefficient of Performance (COP) of 1.7 and subtracted from A/C electrical consumption (ACEEE, 2003). This can be inferred from the energy balance of the building and summarized as follows:

$$Y= [A + B] – [(B + C)/COP]$$

Where:
Y= A/C electrical consumption due to building envelope
A= A/C electrical consumption during cooling season
B= Non A/C electrical consumption during neutral season
C= Heat gain from people
COP = 1.7

The author decided to use the International Performance Measurement & Verification Protocol (IPMVP) for measuring and verifying the energy and cost savings associated with energy conservation measures. IPMVP is adopted by more than 20 countries as the standard for measuring and verifying energy conservation measures (ECMs). It provides an overview of current best practice techniques available for verifying results of energy efficiency, water efficiency, and renewable energy projects in commercial and industrial facilities. It may also be used by facility operators to assess and improve facility performance. ECMs covered in the Protocol include fuel saving measures, water efficiency measures, load shifting and energy reductions through installation or retrofit of equipment, and/or modification of operating procedures (International Performance Measurement & Verification Protocol Committee, 2002).

The IPMVP listed four options for verifying and measuring ECMs. They are used according to circumstances and context of the ECMs. They are as follows:

- Option A: Engineering calculations based on spot measurements
- Option B: Engineering calculations based on short-term monitoring
- Option C: Billing analysis at the whole-building level using statistical techniques
- Option D: Calibrated engineering simulation models

Since the whole-building's monthly bills were available during prior to and post-ECMs years, billing analysis, Option C, was used. Option C has two sub-options. One uses statistical analysis when the expected savings are less than 20%; and the other uses simple mathematical comparison.

The billing cycles are based on the Hijri year (lunar year) that is 11 days less than the Georgian year. Bills are not adjusted; therefore, the monthly peak consumption is not consistent throughout the 14 billing years. The author ranked monthly bills in descending order for the prior to and post ECMs. By ranking, the comparison became better and apparent.

CALIBRATION

The long-term metered data was utilized in establishing the baseline consumption. And the inventory of lighting fixtures and equipments were used to calculate the ratio of Lighting Power Density (LPD) and Equipment Power Density (EPD) of the prior to and post-ECMs. Visual DOE, DOE 2.1E interface, has built-in default values for different types of buildings and occupancies. Single-family building default values were used in the first set of runs. Some of the default values were adjusted when the predicted values differed from the base line metered values. Since the house occupied by another household of different number and equipment after ECMs, the input values were adjusted to match the new family needs. There were two estimated building and system attributes by the author, the ACH for the prior to and post ECMs and the COP of the A/C system. These were used in the final stage of the calibration. The sequence of the calibration is as follows:

- Obtaining the blueprints and inspect the building
- Collecting metered data for years before and after ECM
- Interviewing the previous household for equipment inventory and occupancy characteristics
- Documenting thermo-physical characteristics of the building
- Adjusting input data in prior to ECM until the simulated values in baseline (non-AC electrical load) match the metered values.
- Inputting data in the post-ECM according to inventory, new thermo-physical data and adjusting according to the ratio of pre to post ECM values.
- Adjusting the Energy Input Ratio for cooling to account for loss of A/C efficiency with aging (assumed by the author to be 22% less after the ECM)
- Calibrating the model until baseline values match the metered values
- Comparing monthly and annual data of simulated case to the metered data
- Adjusting input for annual consumption and monthly load.

RESULTS

The predicted summer peak electric load was less than the actual peak load in both cases prior to and post ECMS. But the actual and predicted summer peak load indicated savings of 10.75 and 5.53% respectively (Table 3). When comparing summer average electrical consumption the model predicted higher consumption values in both the prior to and post ECMs. The model over estimated the summer average consumption of the post ECMs by 11.6% (Table 3).

During the calibration process of the model some observations worth mentioning, they are:

Non-A/C load is referred to as base load, indicated small difference between the actual values and predicted values. The actual average of non A/C monthly consumption was 1022 and 1727 kWh for prior to ECMs and post-ECMS respectively. The predicted values were 1023 and 1837 kWh Table 3).

The model under estimated the ECMs summer A/C monthly average by 5.4%, the actual values were 2756 vs. 2615 kWh predicted. The savings in the A/C monthly average is clear after implementing the ECMs.(Table 3).

The actual A/C monthly electrical consumptions showed consistent savings in moths March through October especially in peak month July after implementing ECMs. The exceptions that are the months of November and December where the A/C consumptions is higher and non- existence in prior to ECMs (Figure 2). This can be explained by the higher internal heat gains from equipment and users combined by lower U-values and tighter building envelope.

When comparing the post-ECMs actual and predicted A/C monthly electrical consumption the model predicted consumption all year with peak values in July and lowest values in December, January, and February. The Actual A/C Electric consumption during months March through December with peak in July. When comparing monthly values, the model underestimated the peak month by 21.8% and indicated loads in January and February (Figure 3).

The simulation model predicted peak load different from the actual HVAC in the prior to ECMs case, 17.5 tons actual and 15.5 tons predicted. While in the post-ECMs, the model predicted 8.7 tons vs. 17.5 tons actual, installed (Figure 4). It should be noted that the capacity factor was not applied in the predicted values. The actual, installed system, 17.5 tons is sized after applied capacity factor of 1.3 as practiced in Saudi Arabia. If capacity factor is applied the predicted sized would be 12 Tons instead of 8.7. In other words, if new unit is installed it would be 31% smaller than the existing unit.

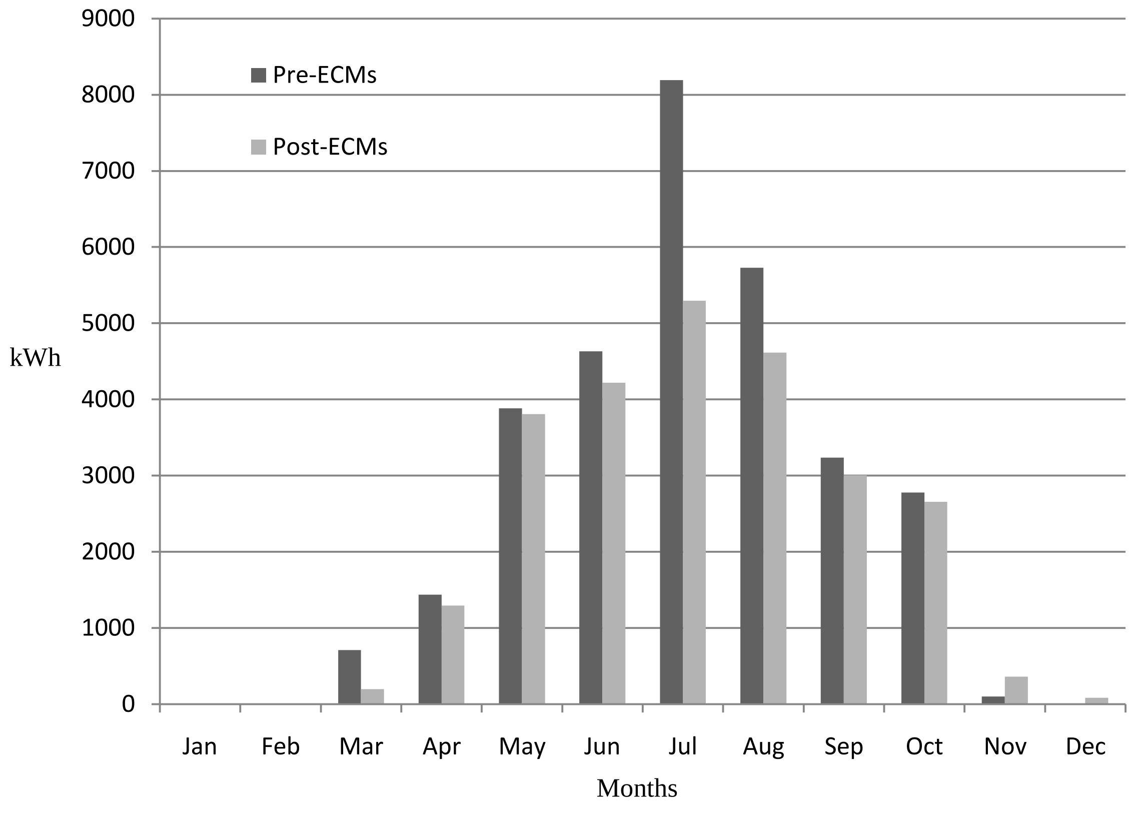

Figure 2: Actual A/C electrical energy in kWh pre and post energy conservation measures (prior to and post ECMs).

Table 3. Summary of electrical energy consumption and associated savings from the analysis of metered data and the model simulation

Items	Prior to ECM		Post-ECM	
	Actual	Predicted	Actual	Predicted
Summer average peak months (kWh)	8855	7995	7023	6655
Difference %		-10.75		-5.53
Summer average months (kWh)	4839	5319	4483	5071
Difference %		9		11.6
Monthly average of non-A/C (kWh)	1022	1023	1727	1837
Difference %		0.09		6
Summer A/C monthly average (kWh)	3817	3845	2756	2615
Difference %		0.7		5.4
Monthly A/C electrical consumption due to bldg envelope (kWh)	3576	3340	2343	2351
Difference %		-7.1		0.34
Peak A/C load Tons	17.5	15.5 *	17.5	8.7*
Difference %		-11.5		-50.1
Peak months A/C consumption due to bldg envelope (kWh)	3567	3270	2343	1870
Difference %		-9.1		-25.3

* capacity factor was not applied

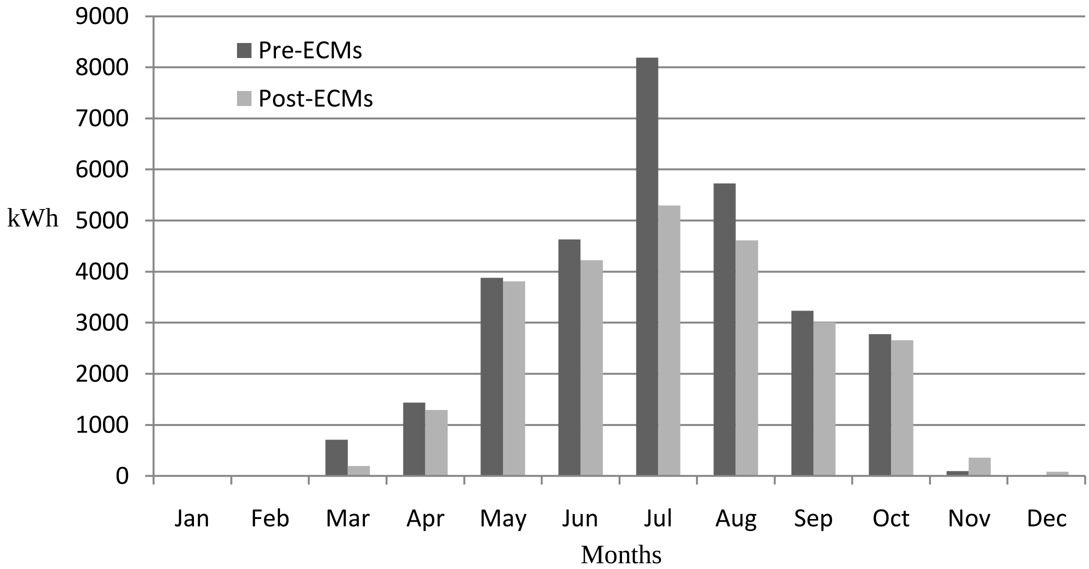

Figure 2: Actual A/C electrical energy in kWh pre and post energy conservation measures (prior to and post ECMs).

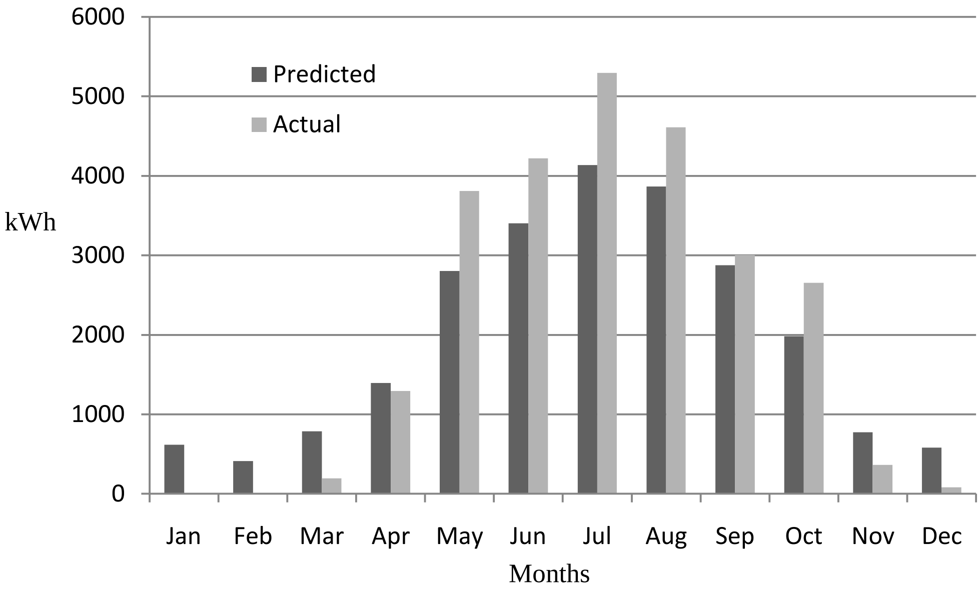

Figure 3: Post-ECMs A/C monthly electrical energy consumption (kWh) actual vs. predicted.

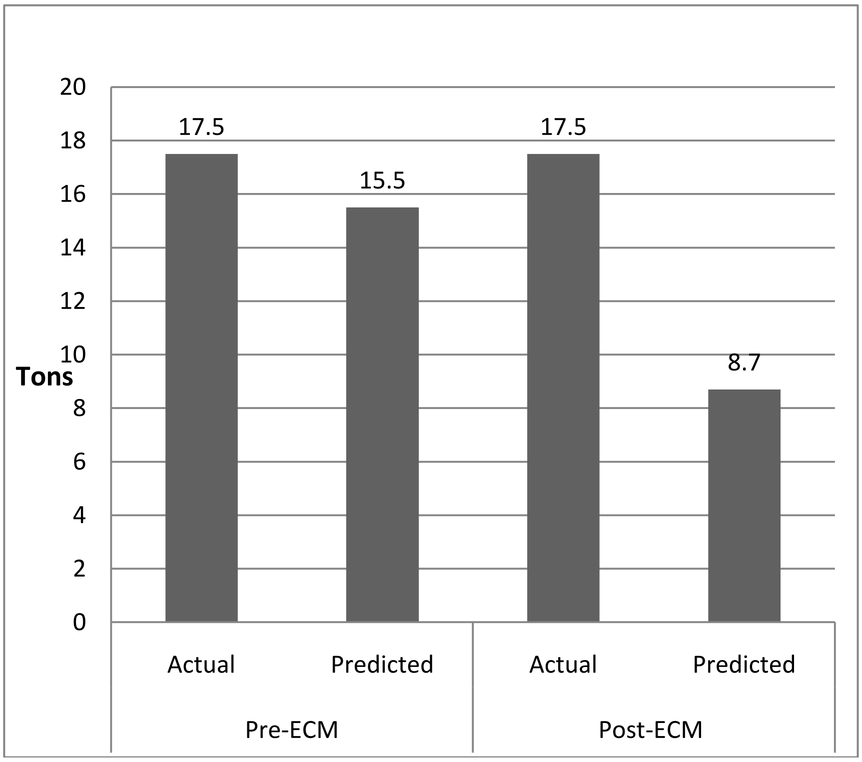

Figure 4: Predicted vs. actual A/C system peak load in tons of refrigeration

DISCUSSION

The differences were expected based on the uncertainty associated with modeling the thermo physical characteristics of the building and its operation (human interaction). Although, during the model calibration, the author tried not to be trapped by compensating errors usually associated with this kind of study, the differences were within the ASHRAE recommended ranges. There were several assumptions made to account for non-weather related factors, such as the hours of lighting and equipment operations during the prior to ECM and post-ECM years. The non-weather related electrical consumption during prior to ECM period was 60% of the post-ECM period. This information helped in deciding on the figures for equipment power density (EPD) used in the simulation.

The assumption of degradation of energy input ratio (EIR) of the cooling system from 2.2 during prior to ECM to 1.7 during the post-ECM period, was instrumental in raising the peak months of the model to match the peak months of the metered months. Since the study did not include the daily metered data, the differences in daily electric load was not reported. This kind of study has minimal control, especially the occupants behavior and schedule not like office buildings were occupants had minimum control. The long-term data used in calibration of the model should be viewed as stabilizing, since monthly data represents six years in both cases prior to and post ECM.

Although the control in this study was minimal, the differences between prior to ECM and post-ECM electrical consumption is significant in the metered kWh analysis and the simulation. The results are comparable with several local and international studies.

CONCLUSION

This study, based on long-term data, reinforces the notion that energy simulation software are vital tools for designers, architects, and engineers during the schematic and final design stages. One must reach the same conclusion when implementing energy conservation measure from actual utility monthly bills or through model simulation. When using DOE 2.1E to model a single family residential building in Saudi Arabia, long-term data can be useful to minimize uncertainty. The predicted monthly average kWh for the post-ECM was very close to the actual metered values. This can be drawn to the predicted summer average peak month consumption within 5.53% from the actual metered value. Residential buildings had many uncontrollable factors that feed the uncertainties.

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